20.2

NOVA PULSE POWER SYSTEM DESCRIPTION AND STATUS

K. Whitham, B. T. Merritt, R. W. Holloway, D. G. Gritton, J. A. Oicles

University of California, Lawrence Livermore National Laboratory, Livermore, CA 94550

Summary

The Nova laser system is designed to produce critical data in the nation's inertial confinement fusion effort. It is the world's largest peak power laser and presents various unique pulse power problems. In this paper, pulse power systems for this laser are described, the evolutionary points from prior systems are pointed out, and the current status of the hardware is given.

Introduction

Inertial confinement fusion is being vigorously pursued at LLNL. The Nova laser system is the latest in a series of increasingly large lasers that have been built to characterize fusion targets and to approach a demonstration of break even. The Nova laser will deliver 300 kJ of 1.06 micron light on target when it is completed. At this time DOE is considering frequency conversion of Nova to 2 and 3ω. The amplifiers for this system use Nd-doped phosphate glass as the amplifying medium. The pump energy to excite this medium is supplied by flashlamps which in turn are driven by energy stored in capacitors. Each lamp pair is driven by a circuit storing from 18 to 50 kJ of energy. The total stored energy for the Nova system is about 100 MJ.

Because of the size of the Nova bank, many areas were studied to reduce cost yet retain needed levels of performance. The one with the most leverage was capacitors. For this component, vendors were solicited and to develop high energy-density capacitors to a specification derived from a statistical study of the desired reliability of the Nova bank.[1]

A second subassembly where significant cost savings were realized was the power supplies. By going to substation-size supplies and placing them outside the laboratory building, savings were realized in economies of scale in the supply and in building space.

The number of components were reduced wherever possible as well. The flashlamp drive system, for example, consists of many circuits grouped around common switches to conserve switch count. Figure (1) illustrates how up to 24 circuits make use of one switch, yet retain individual fuses for isolation.

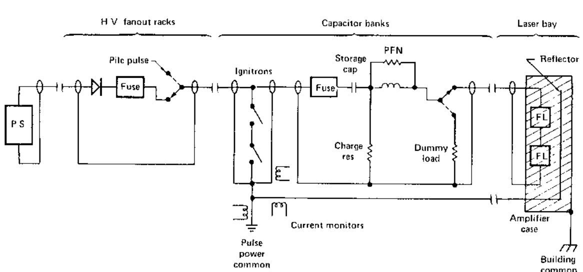


Figure 1: Nova Power Conditioning Circuit

There are many other areas where evolutionary improvements have been made to enhance performance or reduce cost. New high power resistors have been developed, for example, that have ten times the energy absorbing capacity of the earlier versions.

In addition, LLNL has been working with the University of Texas to develop rotary energy storage devices such as the Compensated Pulsed Alternator and the Active Rotary Flux Compressor[2]. The goal of this effort is to provide lower cost energy storage for pulse power. The application these devices will no doubt be in a larger system than Nova, perhaps rep rated.

The flashlamp drive system, however, is not the only pulse power element in the laser, albeit the largest physically.

A major effort in pulse power is directed toward driving the several optical shutters found in each chain. There are three basic types of shutters used. For small aperatures (< 5 cm) Pockels Cells are employed. These are single crystals of KD*P which when placed in an electric field rotate the plane of polarization of incoming polarized light. By placing this crystal between polarizers and switching the electric field, a fast optical switch is created[3]. Switching times in the 1 ns regime are realized using this technique and applications are in the oscillator switch out and in the front end of each laser chain. For optical apertures from 5 to 35 cm, Faraday Rotators are used. These devices use a similar, polarization-rotating technique but employ a magnetic rather than electric field effect. Because of this the Faraday rotator cannot be rapidly switched but instead is used as an optical diode, transmitting forward light down the chain but diverting reflected light into beam dumps. Each Faraday rotator requires a great deal of stored energy for large sizes, eg, 200 kJ for 20.8 cm aperture. Because of the cost of stored energy and the cost of rotator optics, alternative shutters have been studied. The Plasma shutter is such an alternative.[4]

The plasma shutter explodes a wire and puffs it across a pinhole to block reflected light from propagating down the chain. This pulser requires 650 kA of current and <400 ns rise time to obtain the needed closure time.

These devices are discussed further below.

Switching

The Nova energy storage system uses ignitrons for the switch element. In order to insure reliable operation of these tubes, a number of steps have been taken. The most troublesome aspect of ignitrons in a large population used for a system like Nova is their propensity for prefire. New tubes are now bought to a specification that sets a maximum prefire rate under incoming test conditions. In addition, the cathode of each tube is water cooled to 16-18 degrees C, and the anode is heated to 50 degrees C. Anode heating was accomplished in the past by heat lamps. On Nova, direct contact heaters powered by isolation transformers are used. This has reduced the power consumption from 500 watts per tube to 26. In addition, to prevent prefire, two tubes are placed in series in each switch and a voltage divider is used to equalize tube voltage. Periodic high potting to

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1981**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Nova Pulse Power System Description And Status**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, Lawrence Livermore National Laboratory, Livermore, CA 94550**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

25 kV ac is also performed to check the condition of each tube. In order to detect and localize any prefire that might occur, a voltage monitor is placed in each switch rack. This monitor is fiber optic coupled to the control system, so if a prefire occurs the event is immediately recognized and action is taken. Ignitor failure is another failure mode of ignitrons. On Nova, both ignitors on each tube are fired on each shot, and current transformers monitor each trigger. This trigger information is fiber optic coupled to the control system as well, so that failures can be localized and repaired quickly. A large current transformer, called a stem bug, is used to monitor the main switch current as well, so that each switch is fully diagnosed.

In the Nova system, effort was made to separate the power conditioning system physically as much as possible from the laser, both for safety and in order to operate the bank as a separate entity for test and debug. For this reason the bank diagnostic system, LCD, and its sensors, current bugs, are located in the bank. The current bugs are located in the switch and monitor current flowing in the power conditioning ground leg of each lamp circuit. This choice was made to be able monitor all high current fault modes associated with flashlamp circuit failures.

One hundred thirty, dual, size-D ignitron switches are used in Nova I. An integral number of amplifiers must be connected to an individual switch to prevent partial firing of an amplifier's flashlamps and possible damage. The switches are staged so that individual beam lines may be fired. The largest amplifiers have 46 cm aperture for the laser beam and use 80 lamps each connected 5-in-a-series in 16 circuits. Each amplifier uses a single switch assembly. The staging of the amplifiers is shown in Table II.

At present the subassemblies are all designed. Long lead orders have been placed, and orders for ignitrons from three vendors for qualification to the new specification are in process.

Energy Storage Modules

The 100 MJ energy storage requirement for Nova is split into two 50 MJ segments. There exists one module per flashlamp or rotator circuit. A module consists of two to fourteen capacitors, and a pulse forming network (PFN) board. The PFN board consists of a pulse shaping inductor, charge resistor, fuse, damping resistors and dummy load. A typical module is shown in Figure 2.

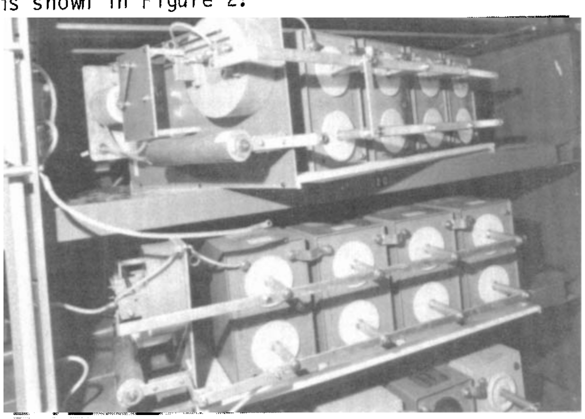


Figure 2: 50 kJ Energy Storage Module

The capacitors used for Nova I are built in 3 kJ, 5 kJ, and 12.5 kJ sizes. The 3 kJ and 5 kJ units will be salvaged from the Shiva and Argus laser systems. The 12.5 kJ units were especially developed for the Nova program. The salient features of these high density capacitors are given in Table I[1]. Basically we have traded capacitor life for energy density. The capacitors physically are all about the same size, i.e., about 175 lbs. As evident from Table I the high energy capacitors, 12.5 kJ units, have much higher operating stresses and correspondingly lower lifetimes.

The modules are sized as nominal 18 kJ, 25 kJ, 37.5 kJ or 50 kJ units for flashlamp applications. The 18 kJ modules are similar to those used on Shiva consisting of six 3 kJ capacitors. The 25 kJ units will consists of two 12.5 kJ units or seven 3 kJ units operated at 22 kV; the 14.5 μF capacitors are rated 3 kJ at 20 kV. The 37.5 kJ units will be three 12.5 kJ units or eleven 3 kJ units run at 22 kV. The 50 kJ units will consist of fourteen 3 kJ cans run at 21.8 kV; these will be used to power the rod amplifier circuits only.

To date we have tested about 120, 12.5 kJ capacitors from three different sources. Our results indicate these capacitors will have a system mean time between failure of at least 100 shots[1], which was our original design goal. This failure level was determined by applying Weibull statistics to our test data. LLNL will purchase about 25 MJ of these capacitors for Nova I at a cost of $0.052/joule.

The staging of the capacitor bank for Nova I is detailed Table II.

At this writing orders for capacitors for Nova I have been placed.

High Power Resistors

Since Shiva, a considerable effort was made to improve the resistors used for the PFN. In particular extensive testing was performed on resistors for use as dummy loads and dumps. The dummy load is an alternate load for the energy storage modules. The dumps are used in the crowbar system to safe the capacitors in the modules. Samples of these resistors are shown in Figure 3.

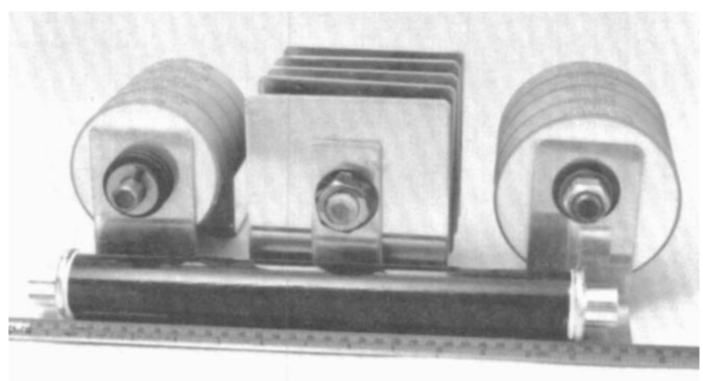


Figure 3: High Power Resistors

The requirements for the dummy load are an impedance of approximately 8 ohms, an energy capability of 50 kJ, and a voltage rating of 22 kV. We have found three different resistors that meet these requirements. The first two types are cermamic disc types - one made by Allen Bradley of England and the other made by Carborundum's Japanese affiliate; the Japanese also have cooling fins. The third type is a tubular ceramic made by Carborundum. All three of these types are capable of absorbing 200 kJ in a single pulse. The resistors have also been tested at 50 kJ per pulse at a five minute repetition rate. The ceramic disc types have achieved thousands of shots before failure. The tubular type has over 1000 shots before failure; this type of resistor should cost significantly less.

The requirements for the dump resistor are an impedance of 1000 to 2000 ohms, an energy capability of 200 kJ single pulse, and a voltage rating of

22 kV. We have tested two types of resistors for this application; a ceramic disc made by Allen Bradley of England and a tubular ceramic made by Carborundum. Both types are capable of absorbing 200 kJ in a single pulse. Both resistors have been tested at 50 kJ per pulse at a five minute repetition rate. Both types have also achieved over 1000 shots before failure.

Power Supplies

To charge the Nova bank within 30 seconds, as required for adequate bank lifetime, 12 to 14 MVA of dc power must be applied to the bank. Large substation sized power supplies have been designed to supply this much power at an efficient cost. Smaller, Shiva-type, 100 KVA supplies will be used to charge the modules for the rod amplifiers and rotators, but most of the bank will be charged by six large supplies located in the substation area outside the Nova lab building.

These supplies are designed as three phase voltage doublers. Each supply is capable of charging 12 MJ of capacitors to 22 kV in thirty seconds. They are powered via a fused disconnect from the 13.8 kV ac power mains. They draw approximately 2.0 MVA peak power. A picture of the prototype Nova power supply is shown in Figure 4.

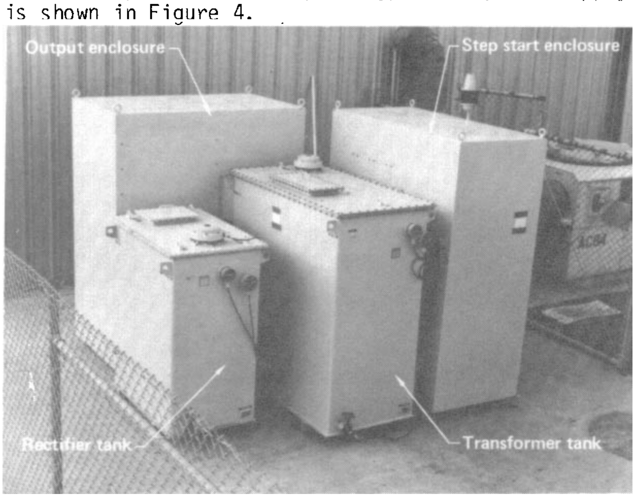


Figure 4: Nova MVA Power Supply

There are differences between these and the Shiva supplies. These MVA supplies are electrically 15 times larger than the Shiva units. They use oil cooled transformers and rectifiers, while Shiva units are all air cooled. The control element is a vacuum contactor on the primary which eliminates costly silicon as on the Shiva units. Due to economy of scale and the use of contactors, the estimated cost of the Nova supplies is $0.08/VA vs $0.15/VA for Shiva (both in constant dollars).

The order for all seven large Nova power supplies has been placed with Aydin engineering of Palo Alto. The first unit is in test at LLNL and has been accepted. The remaining six are to be delivered during calendar '81.

Optical Shutter Pulsers

In order to pulse the Pockels cells in the nanosecond regime, a number of techniques have been used. Pockels cells in the laser chains must each be switched simultaneously. To accomplish this, on Shiva a spark gap was used to switch a parallel group of charged cables into 20 cells. This system worked well but required more maintenance than was desirable for Nova, so the N-way fanout was redesigned to be switched with a hydrogen thyratron. Risetime was degraded from 3-5 ns to 15 ns but for chain Pockels cells the increase in reliability is more important.

In the case of front-end cells, the risetime had to be maintained at 1-3 ns with $<$ 200 ps jitter. For this application, planar triode pulsers were used. The planar triode is a 3000 MHz device which can be operated in a switched mode. In this mode for 5-25 ns pulses the rated cathode current can be greatly extended and a single tube is capable of putting out 30 amperes with several kilovolts of anode swing. A picture of a planar triode driver chassis for a 5 cm Pockels cell is shown in Figure 5.

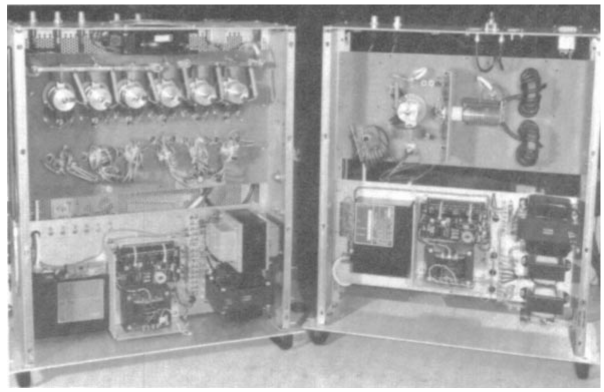


Figure 5: Planar Triode Pulser Chassis

This unit uses 6 tubes in parallel to obtain 1.6 MW of drive power. We have contracted with Varian Associates, supplier of the presently used Y690, to develop a larger diameter cathode to provide more drive current per tube and thus cut down on the number of various places in the laser program.

The Faraday rotator pulse system is very similar to the flashlamp system with the exception that the circuit uses no inductor for pulse shaping. The load is the coil in the rotator body that generates the magnetic field. The LC of the energy storage and the load coil would ring at about 9 kHz if the backswing diode were not used. The ringing would not be deleterious to the rotator's performance since there is sufficient time at the first current peak to satisfy system requirements, but the ringing exchanges a great deal of charge through the switch and many additional switches would be required were the diode not utilized.

The plasma shutter pulse power system has been described in detail in several papers.[4] In summary it utilizes four uv preilluminated rail gaps, low inductance capacitors, elastomer dielectric system, and coaxial geometry to obtain the required 650 kA in 400 ns in a small package that fits in the laser chain. The system has been successfully tested on a Shiva arm and has stopped Nova intensity beams in the time frame required.

Control System

Pulsed power devices in the laser system are controlled and monitored by a computerized system[5], illustrated by Figure 6.

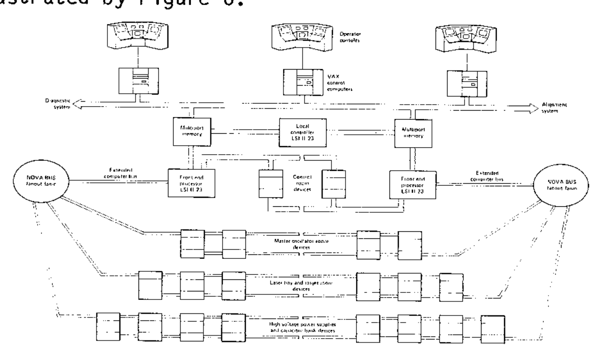
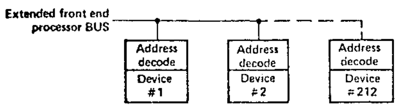


Figure 6: Power Conditioning Control System

The control computer, a DEC VAX-11/780, interfaces with the operator via a system of touch panels and color graphic displays. The operator controls the system by touching a CRT displaying a "menu" of control options. The VAX computer responds to the operator's touch by generating a series of commands to the hardware devices. These commands are put in a memory shared with the front-end-processors (DEC LSI-11/23 microprocessors) which in turn routes the command to the desired hardware. The FEP constantly polls the hardware devices for status information which is stored in the memory shared with the control computer. Thus, the control computer has visibility of the overall system at all times.

Pulsed power devices are connected to the FEP's in a redundant fashion as shown in Figure 6.



Novette	Nova ϕ_1	Nova	
–	7	14	MVA HV power supplies
16	12	21	100 KVA HV power supplies
–	7	14	HV distribution racks (fanouts)
9	31	61	Ignitron switch groups (1-5 ign pairs/group)
9	31	61	Lamp circuit diagnostics
6	13	23	Laser bay and target room diagnostic/trigger units
–	10	10	Plasma shutter
2	2	2	Safety interlocks interface
3	6	6	Master Oscillator room devices
45	119	212	Total devices

Figure 7: Novabus Device List

The FEP's internal bus is serialized and extended to service numerous devices listed in Figure 7 The interconnection network is called Novabus and divides the devices among 12 parallel chains.

Communication between the computers and the pulsed power devices must take place in a hostile environment of high voltage, high currents, and extreme EMI fields. Additionally, the communication system must provide isolation between devices. Using fiber optics as a communication medium resolves the isolation requirement but does not satisfy the noise immunity requirements. Optical commmunication is inherently immune to EMI but the conversion process from optical to electrical is noise sensitive. This is especially true if the data rate (bandwidth) is high and the optical flux is of low intensity. The Nova control system operates at 10 Mbps with an optical flux of 10 watt. Shielding of the optical receiver has been tried with limited success. The resolution of the noise immunity problem for Nova is to store command schedules to occur at peak noise periods in the device interface electronics. Thus during the time of high noise levels, optical to electrical conversion errors do not effect operation of the system.

Long lead components are on order. Most design is complete and prototype hardware is built and in test in a 1 MJ test bank at LLNL.

*Work performed under auspices of DOE by LLNL under contract No. W-7405-Eng-48.

References

1. B. Merritt and K. Whitham, "Performance and Cost Analysis of Large Capacitor Banks Using Weibull Statistics and MTBF".
2. B. Carder, E. Goodwin, D. Eimerl and J. Trenholm, "Optimized High-Power Compulsator Designs".
3. J. Oicles, D. Downs and D. Kuizenga, "Fast Versatile Pockels Cell Driver".
4. L. Bradley, E. Orham, I. Stowers and P. Koert, "Development of a Plasma Retropulse Shutter for Shiva and Nova".
5. 1979 Annual Report - Pulse Power Section, Vol. 1, pp 92-106.

TABLE I

STRESS LEVELS AND NOMINAL LIFE SPANS OF CAPACITORS.

	14.5 F	25 F	52 F	52 F
Operating Voltage (kV)	20	20	22	22
Energy Storage (kJ)	2.9	5	12.5	12.5
Number of Series Sections	4	2	2	2
Voltage Per Section (kV)	5	10	11	11
Operating Stress (kV/mil)	2083	2564	5000	3333
Dielectric Type	Paper/ castor oil	Paper/ castor oil	Paper/ poly/dop	Paper/ castor oil
DC Life (h)	2000	1200	1000	1000
Pulsed Life[a] (shots)	10^6	500,000	200,000	200,000

[a]Nonreversal (3 kA)

TABLE II

CAPACITOR BANK STAGING

Component	# Total	Circuits per Component	Circuits Total	Energy per Component	Energy per Circuit	Energy Total	Lamps per Circuit	Lamps Total
Rod	16	1	16	50	42*	672-3 kJ	6	96-19"
9.4 Disc	20	8	160	144	18	2880-3 kJ	2	320-44"
9.4 F.R.	12	1	12	21	21	252-8 kJ		
15 F.R.	10	4	40	100	25	1000-12.5 kJ		
15 Disc	10	12	120	216	18	2160-3 kJ	2	240-44"
20.8 F.R.	10	5	50	200	40	2000-5 kJ		
20.8 Disc	30	8	240	200	25	6000-12.5 kJ	2	480-44"
31.5 F.R.	10	5	50	200	40	2000-5 kJ		
31.5 Disc	40	10	400	375	33*	13200-3 kJ	2	800-44"
46 Disc	30	16	480	600	37.5	1800-12.5 kJ	5	2400-19"
	Total # Circuits =		1568	# 12.5kJ Capacitors =	2000	or 25000 kJ		2496-19"
	# Rotator Circuits =		152	# 5kJ Capacitors =	800	or 4000 kJ		1840-44"
	# Lamp Circuits =		1416	# 3kJ Capacitors =	6388	19164 kJ		
						48164 kJ = Total Bank Energy		

*Operated at 22 kV